National Aeronautics and Space Administration

YEARS 1-3 *EXECUTIVE SUMMARY*

The Moon as Cornerstone to the Terrestrial Planets

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NASA LUNAR SCIENCE INSTITUTE

8. Brown/MIT Team: The Moon as Cornerstone to the Terrestrial Planets

8.1. Short Summary: NLSI at Brown/MIT

Our Brown/MIT NLSI node is jointly hosted by Brown University and the Massachusetts Institute of Technology by faculty who share a long history of science interactions. Our combined team began with 19 Co-investigators and 13 named Collaborators from 8 institutions. The flexible structure of NLSI has allowed some scientists to move in and out of this group over the last three years, while the team as a whole has remained active and focused. Productivity enabled by NLSI continues to grow. The components central to our NLSI team include four specific science themes that build on our strengths, four pillars that form our integrated implementation plan, and a strong infrastructure of laboratories and facilities that supports these lunar science activities.

NLSI Brown/MIT Team Citations and Presentations for 2009-2012

For the integrated projects carried out by the Brown/MIT team we have compiled publications lists of (1) articles that appear in peer reviewed literature as a product of our NLSI, and (2) extended abstracts that result in presentations made at scientific meetings or conferences derived from NLSI related activities. These two types of supporting information are listed separately in the attached bibliography that covers 2009 to March 2012. NLSI science publications of the PI, Institutional PI, Co-I's, their postdocs and students, and Collaborators are listed alphabetically by year and are summarized in the table below.

Students carry out a variety of lunar related projects and are encouraged to actively participate in on-going lunar missions as part of their scientific education and experience. If mission participation results in student-led lunar research and the student is the first author, those efforts are included as part of this NLSI report. All publications led by a student as first author are indicated by the <u>student Name being underlined</u>.

To date, activities associated with our NLSI activities have resulted in **74** separate peer-reviewed articles and **146** extended abstracts/presentations contributed by the Brown/MIT NLSI PI, Institutional PI, Co-I's, their postdocs and students, and Collaborators. Of these, **27** of the peer-reviewed papers and **61** of the extended abstract/presentations are <u>led by</u> <u>students</u>.

Since the Brown/MIT PI, Institutional PI, and several CoI's have been active members of a lunar mission team, several valuable publications have also been produced that are not the direct result of NLSI activities. Such mission-related citations are listed and accounted separately. Although NLSI members lead or participate as named co-authors on such mission papers, abstracts and presentations, these **30** articles and **60** lunar abstracts are *not* included in the NLSI related publications that are summarized and discussed in this report. We nevertheless attach a separate list of lunar mission-related citations and extended abstracts produced by our team because they may be of interest to the community as a whole even though they are *not* considered part of this NLSI report.

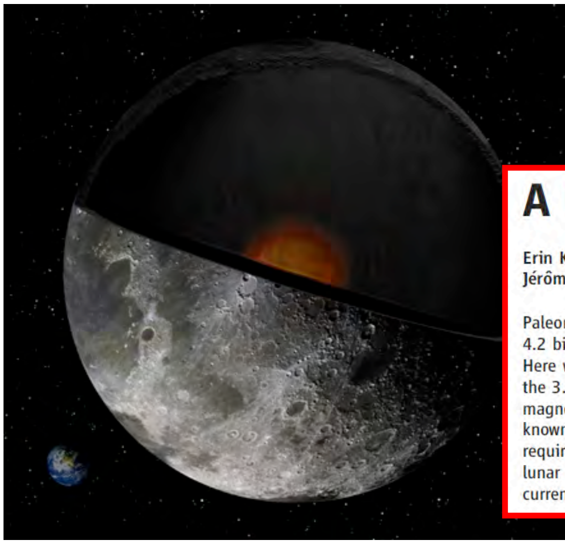
Table 8.1. Publications of the Brown/MIT NLSI team resulting from NLSI activities.

Year	# Peer-reviewed [Student led]	# Extended Abstracts [Student led]	*# Mission Peer-reviewed*	*# Mission Extended Abstracts*
2009	16 [8]	9 [1]	*4*	*6*
2010	21 [2]	47 [16]	*4*	*29*
2011	23 [9]	41 [22]	*17*	*16*
2012*	14 [8]	49 [21]	*5*	*9*
Totals	74 [27]	146 [61]	*30*	*60*

*to date

Recent examples from our Science Themes and Implementation Plan are highlighted here, but discussed in more detail in the documents and publications resulting from this work (see attached bibliography) as well as the body of the report.

Accurately constraining early interior processes of the Moon is an important but difficult challenge. Some of the most recent successes have come from extracting the paleomagnetic record from carefully chosen well-characterized lunar samples using modern equipment. A highly



A Long-Lived Lunar Core Dynamo

Erin K. Shea,[1*] Benjamin P. Weiss,[1] William S. Cassata,[2] David L. Shuster,[2,3] Sonia M. Tikoo,[1] Jérôme Gattacceca,[4] Timothy L. Grove,[1] Michael D. Fuller[5]

Paleomagnetic measurements indicate that a core dynamo probably existed on the Moon 4.2 billion years ago. However, the subsequent history of the lunar core dynamo is unknown. Here we report paleomagnetic, petrologic, and $^{40}Ar/^{39}Ar$ thermochronometry measurements on the 3.7-billion-year-old mare basalt sample 10020. This sample contains a high-coercivity magnetization acquired in a stable field of at least ~12 microteslas. These data extend the known lifetime of the lunar dynamo by 500 million years. Such a long-lived lunar dynamo probably required a power source other than thermochemical convection from secular cooling of the lunar interior. The inferred strong intensity of the lunar paleofield presents a challenge to current dynamo theory.

significant result was recently published in *Science* with MIT graduate student Erin Shea as first author (Vol 335 27 January 2012). The NLSI team has provided solid evidence not only that the Moon had a significant core and dynamo, but that the dynamo was active at least until 3.7 billion years ago (when many mare basalts were emplaced).

The origin, character, and distribution of lunar water have not only sparked great public interest and curiosity, but analyses of these properties have enormous scientific value. Our NLSI team has been involved with all forms of water discovered on the Moon. First, in 2008 Saal et al. reported the first measurement of lunar water and new volatile contents (H_2O, F, S, Cl) in single lunar glass beads and concentration profiles across beads of very-low-Ti glasses. In volatile-volatile plots the concentration profiles in a single bead implied a degassing processes. Degassing model suggested an initial water concentration of ~ 750 ppm, with a minimum of 260 ppm at the 95% confidence level. Probing further, in 2011 the same group reported volatile contents in lunar melt inclusion (inclusions within crystals within glass of the primitive melt) confirming our early predictions that the volatile contents of lunar volcanic glasses were equivalent to those found in MORB (Hauri et al., *Science*, 2011). This new study includes scientists from two NLSI centers as well as students.

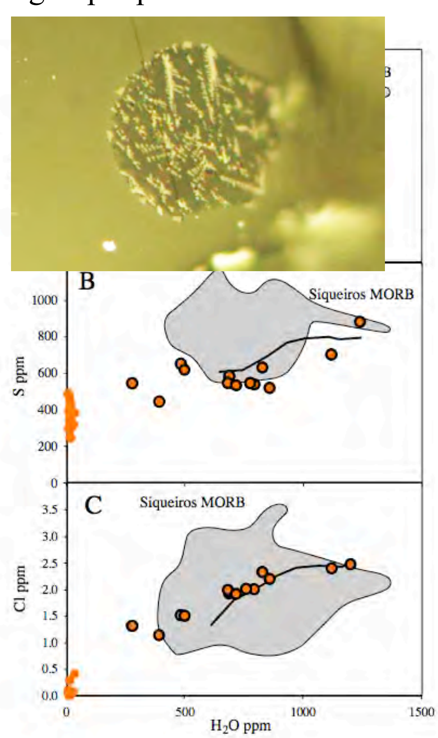


Figure 8.1. Volatile content of melt inclusions (Hauri et al., 2011)

High Pre-Eruptive Water Contents Preserved in Lunar Melt Inclusions

Erik H. Hauri,[1*] Thomas Weinreich,[2] Alberto E. Saal,[2] Malcolm C. Rutherford,[2] James A. Van Orman[3]

The Moon has long been thought to be highly depleted in volatiles such as water, and indeed published direct measurements of water in lunar volcanic glasses have never exceeded 50 parts per million (ppm). Here, we report in situ measurements of water in lunar melt inclusions; these samples of primitive lunar magma, by virtue of being trapped within olivine crystals before volcanic eruption, did not experience posteruptive degassing. The lunar melt inclusions contain 615 to 1410 ppm water and high correlated amounts of fluorine (50 to 78 ppm), sulfur (612 to 877 ppm), and chlorine (1.5 to 3.0 ppm). These volatile contents are very similar to primitive terrestrial mid-ocean ridge basalts and indicate that some parts of the lunar interior contain as much water as Earth's upper mantle.

Secondly, the discovery of widespread lunar surficial OH/H2O, whose origin appears to be linked to solar wind processes [Pieters et al., Science, 2009], sparked new directions in lunar sample investigations as well as new detailed compositional analyses of lunar terrains with remote data. Some of the new analyses are led by our NLSI team members, but the interest spans the community as a whole. Using the now public M^3 data, we have identified a few local areas on the lunar surface that are extremely water-rich. The most prominent are found on the farside and manuscripts discussing the implications of this discovery for lunar crustal evolution are in preparation. All other conditions being equal, a generic association of OH with composition has been found that is likely due to mineral physics processes. Specifically, mafic-rich basaltic areas do not attract much OH/H2O, whereas anorthositic areas are highly correlated with surficial OH/H2O. This relation is illustrated in Figure 8.2 [see student report: Cheek et al., lpsc 2012].

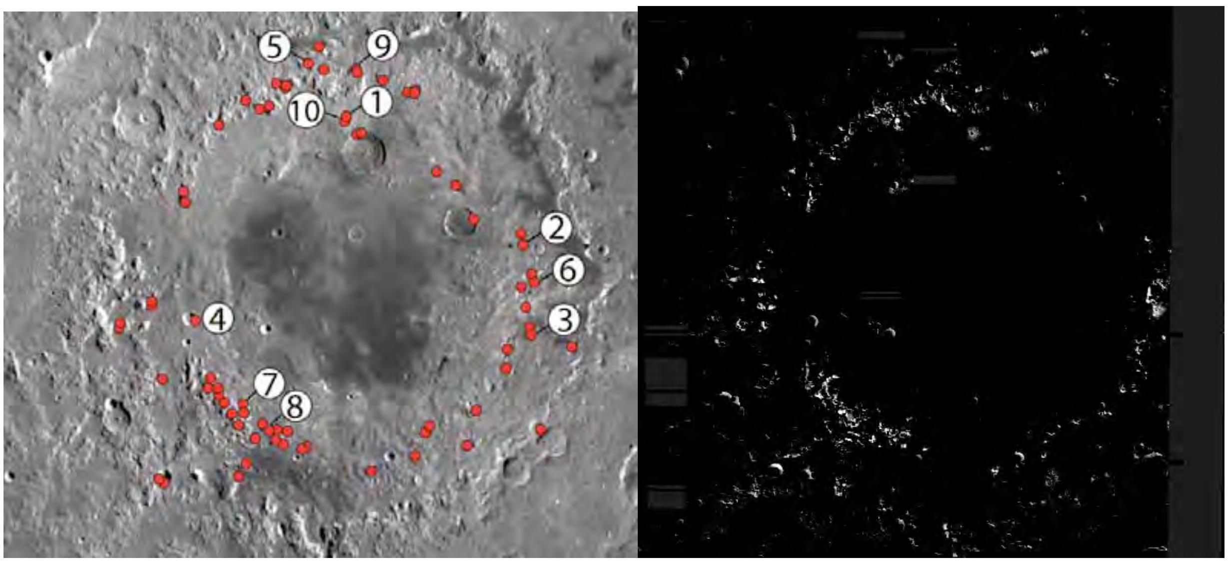
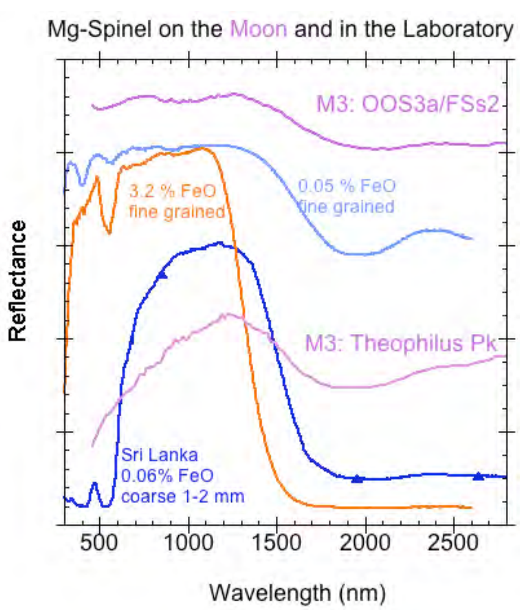


Figure 8.2. [Left] Outcrops of crystalline anorthosite identified in the Orientale region with M3 data based on a highly diagnostic 1.25µm absorption feature (Cheek et al., 2012). The pure anorthosite is massive and concentrated along the Inner Rook Mountains. [Right] Band depth for OH feature at 2.8µm across the Orientale region derived from M3 data. The presence of OH is highly correlated with massive anorthosite.

The discovery of a *new* lunar rock type that is dominated by Mg-spinel has created intense interest and discussion. Its geologic setting implies it is associated with deep-seated crustal material, and several independent experimental programs have been initiated across the community to characterize this new rock type and constrain crustal evolution.



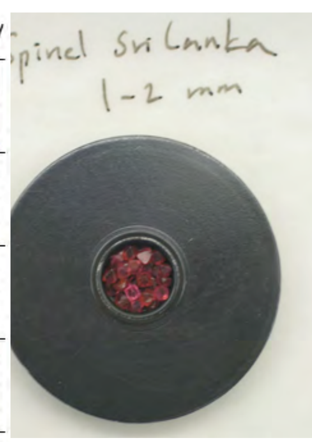
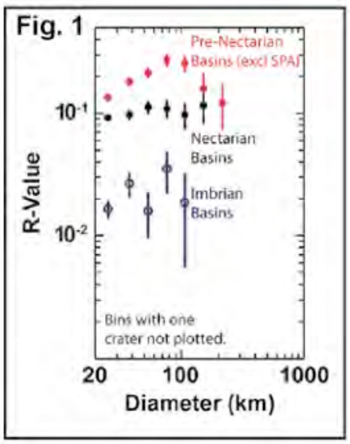


Figure 8.3. Spectra of Mg-spinel measured on the Moon by M3 (shown in purple) and example laboratory experiments designed to constrain the amount of FeO present (see student report by Jackson et al., lpsc 2012).

The Moon has retained the record of the bombardment history for our part of the solar system at 1 AU. The high accuracy of LRO LOLA data has allowed properties of craters to be measured unambiguously across the Moon. Derived crater size-frequency distributions (CSFDs) shown in Figure 8.4 for Pre-Nectarian, Nectarian, and Imbrian basins allow the bombardment history of different epocs to be evaluated and compared (Head et al., 2010). Nectarian basins have a distribution consistent with the late Population 2 impactors (mare-like). The Pre-Nectarian basins, however, are more similar to the early Population 1 impactors. This suggests a transition from predominantly Population 1 to Population 2 impactors must have occurred by the mid-Nectarian in this part of the solar system (Fassett et al., 2012).



Global Distribution of Large Lunar Craters: Implications for Resurfacing and Impactor Populations

James W. Head III,[1*] Caleb I. Fassett,[1] Seth J. Kadish,[1] David E. Smith,[2,3] Maria T. Zuber,[2,3] Gregory A. Neumann,[3] Erwan Mazarico[2,3]

By using high-resolution altimetric measurements of the Moon, we produced a catalog of all impact craters ≥20 kilometers in diameter on the lunar surface and analyzed their distribution and population characteristics. The most-densely cratered portion of the highlands reached a state of saturation equilibrium. Large impact events, such as Orientale Basin, locally modified the prebasin crater population to ~2 basin radii from the basin center. Basins such as Imbrium, Orientale, and Nectaris, which are important stratigraphic markers in lunar history, are temporally distinguishable on the basis of crater statistics. The characteristics of pre- and postmare crater populations support the hypothesis that there were two populations of impactors in early solar system history and that the transition occurred near the time of the Orientale Basin event.

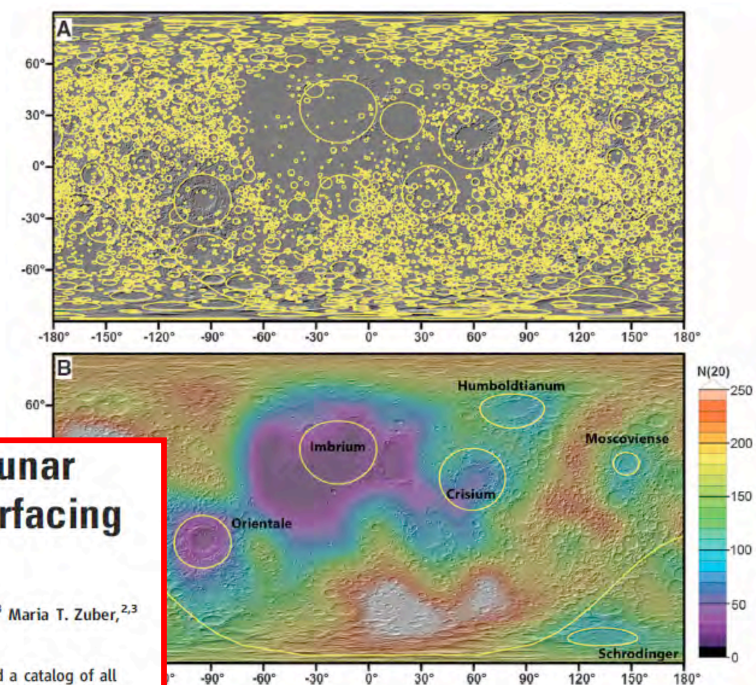


Figure 8.4. *Left:* Relative CSFDs comparing lunar basin environment (Fassett et al., 2012). *Right:* Distribution of craters ≥20 km derived from LRO LOLA data (Head et al., 2010).

The Brown/MIT NLSI **TEAM** is committed to the philosophy that '**T**ogether **E**veryone **A**chieves **M**ore'* and works closely together to execute a dynamic Education and Public Outreach (E/PO) program in support of the NLSI, as coordinated by the NLSI Central Office. The E/PO team is committed to supporting a unified lunar E/PO program for NASA and the NLSI. Four E/PO goals have guided our efforts and directly support NASA's E/PO outcomes (e.g., NASA DRAFT Ed Mgmt Plan, p. 9, Jan. 2006); Table D1): 1) Rekindle humankind's sense of wonder with the Moon, 2) Inspire and motivate the next generation of lunar explorers, 3) Broaden student knowledge of the early Earth-Moon history, 4) Increase underrepresented / minority participation in exploring the Moon. The breadth of our program and examples of each component are documented in our full E/PO report.